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PATENT APPLICATION

OPTICAL SIGNAL CONVERTER WITH FILTERED OUTPUT

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CROSS-REFERENCES TO RELATED APPLICATIONS

This application claims priority from U.S. Provisional Patent Application Serial No. 60/249,496, filed November 16, 2000, entitled "OPTICAL FILTER," the disclosure of which is hereby incorporated by reference in its entirety.

BACKGROUND OF THE INVENTION

The present invention relates generally to components and devices in fiberoptic communication networks, and more particularly, to optical signal generators with filtered outputs which are very useful in such networks.

Most fiberoptic networks today use wavelength, or frequency, to define a communication channel in the network. These channels for such WDM (Wavelength Division Multiplexing), or more currently, DWDM (Dense Wavelength Division Multiplexing) fiberoptic networks are defined by the ITU (International Telecommunications Union) in the 1550nm wavelength range for transmitting and receiving information over optical fibers. Depending upon the particular network, these channels are separated by differing amounts. For example, WDM networks have a 200GHz frequency separation and the more modern DWDM networks have a narrower 100GHz separation. In passing, it should be noted that the terms, WDM and DWDM, are meant to be used interchangeably unless clearly differentiated as in the previous sentence.

Given these defined grids of communication channels, wavelength (or frequency) conversion is a very useful operation in such networks. Signals of one wavelength (or frequency) channel can be converted to signals of another wavelength channel. One device which is emerging as a frequency converter is the difference frequency generator (DFG). The signals of the frequency to be converted are sent as input to the DFG, which also receives an energizing pump signal. The DFG converts the input signal to an output signal at a frequency dependent upon the frequencies of the input signal and pump signal. However, at the output of the device or DFG process there may be signals at both input and output frequencies due to incomplete conversion or other phenomena. It is desirable to be able to separate the input and output frequencies (or wavelengths) from each other.

The present invention provides for wavelength conversion and separation of outputs without a typical filter device which must be tuned or adjusted depending on the value of the wavelengths involved or which must be made specifically for, and hence only work properly for, a predetermined wavelength(s). This avoids complexity, provides for increased reliability and lowers costs of manufacture and maintenance.

SUMMARY OF THE INVENTION

The present invention provides for an optical signal converter which converts signals at one frequency to signals at another frequency within a frequency grid in which each adjacent pair of frequencies in the frequency grid are separated by a predetermined amount. The optical signal converter has a difference frequency generator and a separator. The difference frequency generator receives an energizing pump signal and an input signal at a first frequency and generates a converted signal at a second frequency from the input signal and the pump signal. The pump signal is set at a frequency such that the first and second frequencies are separated by an odd multiple of the predetermined amount. The separator has an input port and at least one output port with the input port connected to the difference frequency signal generator. The separator is responsive to the odd multiple separation and transmits the converted signal to the output port so that the converted signal is separated from said input signal. The optical signal converter can receive more than one input signal to generate a plurality of corresponding converted output signals. Similarly, more than one pump signal (at different frequencies but with the relationship above) can generate a plurality of converted output signals.

More specifically, if the pump frequency is such that one-half of the pump frequency is one-half between two frequencies of the frequency grid, a WDM interleaver multiplexer/demultiplexer may be used for the separator.

BRIEF DESCRIPTION OF THE DRAWINGS

Fig. 1 is a representation of a DFG with input signal, pump signal and output converted signal;

Fig. 2 illustrates a portion of an exemplary WDM frequency grid;

Fig. 3 illustrates the transmission characteristics of a frequency separation device;

Fig. 4 is a block diagram of a difference frequency generator and a frequency separation device, according to one embodiment of the present invention;

Fig. 5A is a block diagram of the Fig. 4 combination with a switch according to the present invention ; Fig. 5B is a block diagram of a pair of Fig. 4 combinations with different connections to the device output ports

Fig. 6A is a block diagram of another embodiment of the present invention by which converted signals at all frequencies are sent to one output port; Fig. 6B illustrates the conversion of input signals at even and odd frequencies by the Fig. 6A optical signal converter; Fig. 6C illustrates the conversion of a range of input signals in which the mirroring frequency is within the range;

Fig. 7A is a block diagram of another embodiment of the present invention by which converted signals at all frequencies are sent to one output port; Fig. 7B is a block diagram of still another embodiment of the present invention by which converted signals at all frequencies are sent to one output port; and

Fig. 8A is a block diagram illustrating the operation of an even/odd combiner according to the present invention; Fig. 8A is a block diagram illustrating the operation of an even/odd separator according to the present invention.

Fig. 9 illustrates the conversion of a set of frequencies when $f_p/2$ lies ¼ way between the frequency grid spacing;

Fig. 10A shows the use of a frequency separation device to separate input signals from converted signals when $f_p/2$ lies ¼ way between the frequency grid spacing; Fig. 10B shows the use of a frequency combiner device to separate input signals from converted signals when $f_p/2$ lies ¼ way between the frequency grid spacing; and

Fig 11 shows the use of a DFG and frequency combiner device to combine a second set of input signals with a first set of input signals which has been shifted by ½ the grid spacing.

DESCRIPTION OF THE SPECIFIC EMBODIMENTS

A representation of a DFG (Difference Frequency Generator) is illustrated in Fig.1. The DFG 10 can receive an input signal 11 and an energizing pump signal 12 to generate a converted signal 13 corresponding to the input signal. The details of DFGs are beyond the scope of this application, but there are references with such details. For example, see Chou, Ming-Hsieu, "Optical Frequency Mixers Using Three-Wave Mixing For Optical Fiber Communications," Ph.D. thesis, Stanford University, August 1999, which describes a periodically polled lithium niobate waveguide.

The frequency (or wavelength) of the output converted signal 13 is related to the frequencies of the input signal 11 and pump signal 12. The energizing pumping signal is at frequency f_p and the input signal at a lower frequency f_s. The output signal has a frequency f_c and corresponds to the input signal and has a certain frequency (and energy) relationship to the pump signal frequency f_p and input signal frequency f_s given by:

$$f_c = f_p - f_s$$

The frequencies f_s and f_c should be within the WDM channels.

However, besides the converted signal at frequency at f_c, the DFG may also have additional output signals at other frequencies. Especially of concern are unconverted input signals as shown by the dotted arrow in Fig. 1. In accordance with the present invention, the output from the DFG is separated at a plurality of output ports according to whether they are input or output signals. The signals of the input and output signals are not sent to the same output port and, in a sense, a static and passive "filtering" operation which is simple and flexible is provided.

This is possible because the DFG is operated in a way that insures that the input and output wavelengths differ in a way that a separation device can recognize. The DFG is operated in a particular way that always converts an input signal of "even" frequency to a converted signal of an "odd" frequency and vice versa. This creates an advantageous combination of simplicity and flexibility.

A detailed explanation of the present invention can perhaps be best understood in the context of a WDM frequency grid. In WDM fiberoptic networks, the communication channel frequencies are defined as combs of evenly spaced frequencies about a center frequency corresponding to a wavelength approximately equal to 1545 nm. The frequency spacing Δ can be 200GHz, 100GHz, 50GHz, etc.

In terms of the given frequency spacing Δ and the resulting WDM comb of frequencies, the input signal frequency to the DFG can be written as

$$f_s = f_o + n_s\Delta \qquad \text{where } n_s \text{ is an integer}$$

about an arbitrary reference frequency f_o in the WDM comb or grid of frequencies. This, of course, places f_s in the WDM comb of frequencies also. Likewise, to keep the converted signal within the WDM comb, the frequency of the converted signal f_c is written as:

$$f_c = f_o + n_c\Delta \qquad \text{where } n_c \text{ is also an integer}$$

With reference frequency f_o in the WDM comb of frequencies, the frequency f_p of the pump signal can be arbitrarily defined with respect to f_o as:

$$f_p = 2f_o + n_p\Delta \qquad \text{where } n_p \text{ is an integer}$$

or rewritten as:

$$f_p/2 = f_o + (n_p/2)*\Delta$$

As stated above, the DFG has the following relationship between the frequencies of the input signal, the output converted signal, and the pump frequency:

$$f_c = f_p - f_s$$

By substitution, this leads to:

$$f_o + n_c\Delta = (2f_o + n_p\Delta) - (f_o + n_s\Delta) \qquad \text{or}$$

$$n_c = n_p - n_s$$

Thus there is a relationship between the various integers based upon the evenness or oddness of the numbers, where evenness or oddness is defined by the common mathematical convention that integers evenly divisible by 2 (including zero) are termed "even", and integers not evenly divisible by 2 are termed "odd". For the possible combinations of n_s and n_p, n_c must be an even or odd as shown by the following Table 1:

n_c	n_s even	n_s odd
n_p even	even	odd
n_p odd	odd	even

Table 1: Evenness/Oddness of n_c

We can see that assuming n_p is odd, n_c is odd if n_s is even, and if n_s is odd then n_c is even. If n_p is odd, one-half of the pump frequency f_p, or $f_p/2$, does not lie on the frequency grid, but rather between the grid. Stated differently, with n_p odd, the input signal frequency and output converted signal frequency are separated by an odd integer multiple of the grid spacing Δ.

This relationship is useful because there are a number of devices that have periodic properties (in frequency) of transmission, reflection, or output port designation. For example, JDS Uniphase of Ottawa, Ontario, Canada and San Jose, California provides WDM interleavers which provide outputs to two or four output ports for output signals separated by

200GHz, 100GHz and 50GHz. These WDM devices accept WDM signals at an input port and separate them at the output ports so that no two signals with neighboring grid frequencies are passed through the same port. Many of these devices are interferometric in fundamental nature, and internally are Mach-Zehnder interferometers, Fabry-Perot interferometers, arrayed waveguide gratings, devices based on crystal-based Fourier filter technology, etc. These commercial products are called interleavers, as noted above, or multiplexers (demultiplexers when used in reverse) for their applications in a fiberoptic network and are typically made specifically to separate the frequencies of the 1550nm telecom bands.

These frequency separation devices, be it by transmission, reflection, or output port, receive either even or odd frequencies through a single input port, and transmit them out on one output port if even, and a second output port if odd. The device has transmission properties as illustrated by Fig. 3. As can be seen, the transmission properties are periodic to two different ports with a period of 2Δ. The device can be termed an even/odd separator and is combined with a DFG device, according to one embodiment of the present invention as shown in Fig. 4. A separator 15 is connected to the output of a DFG 10. The separator 15, as explained above, has two output ports. If n_p is odd, the signals at frequencies f_c and f_s come out on different ports, as in the table below:

	f_s even	f_s odd
port 1	f_s	f_c
port 2	f_c	f_s

Table 2: Output Signals on Ports 1 and 2 Depending Upon fs Even or Odd

For f_s is even, f_s exits on port 1 and f_c on port 2. For f_s is odd, f_s exits on port 2 and f_c on port 1. In either case, the input signal at f_s is separated from the converted signal at f_c.

Control over which output contains the converted output f_c can be done with different techniques. Fig. 4 shows an optical switch 16 which is connected to the output ports of the separator 15. Responsive to a control signal, the switch 16 selects whether port 1 or port 2 of the separator 11 goes to the converted signal output port of the complete system 17. The switch selection depends on whether f_s is even or odd, as shown in Fig. 5A. Alternatively, a pair of devices as shown in Fig. 5B can be constructed in one system 19. One device with its elements denoted with the suffix A has port 2 as the converted output

port and a second device its elements denoted with the suffix B has port 1 as the converted output. Choice of which of device to use depends on whether the input signal frequency f_s is even or odd, as shown in Fig. 5B.

It is possible that the pump light for the DFG process, at $f_p = 2f_o + n_o\Delta$, may be generated within the same device by second harmonic generation (SHG) of an original pump signal at frequency $f_p/2 = 2f_o + n_p/2*\Delta$. That is, while the actual pump signal is at $f_p/2$, the energizing pump frequency for the DFG process is still f_p. Also note that in the case of pump generation by SHG in the same device as the DFG, there may be an issue of separating the signals at $f_p/2$ from the converted output as well. If the transmission curves in Fig. 3 of the separator can be made to fall off more sharply from their peaks, it may be possible to use the same arrangement as well.

Likewise, as in the case of SHG:DFG process described immediately above, the present invention is still effective even with four-wave mixing (FWM). Again, while the pump signal is at $f_p/2$, the two pump signal photons in the FWM process supply energy equivalent to one photon at frequency f_p. The same relationship described above between frequencies of the converted signal, the input signal and the energizing "pump" signal is still applicable, i.e.:

$$f_c = f_p - f_s$$

In other words, the frequency $f_p/2$ of the actual pump signal can be set between the frequency grid so that n_p (for the frequency f_p) is odd and the input signal frequency and output converted signal frequency are separated by an odd integer multiple of the grid spacing Δ. Hence it should be understood, that term, DFG, difference frequency generator (or generation), is used inclusively for DFG alone, SHG:DFG and FWM processes. By ensuring that the frequency f_p is as described above, the "DFG" converts the input signal of one frequency type to an output signal of the other frequency type.

It should be also noted that if the DFG (which includes devices with SHG:DFG processes) is implemented as a periodically polled lithium niobate waveguide as described above, the operation of such devices is sensitive to the polarization of the optical signals. This is undesirable and techniques to ensure the insensitivity of the DFG to polarization are described in the literature. For example, see Chou, Ming-Hsieu *et al.*, "Optical Signal Processing and Switching in Second-Order Nonlinearities inWaveguides,"

IEICE Trans. Electron., Vol. E83-C, No. 6, June 2000, pp. 869-874. Such techniques can be incorporated into the DFG devices described, in accordance with the present invention.

As described above, the optical signal converter converts an input signal of even (odd) frequency and converts it to a signal of odd (even) frequency. The converter separates the signals of even and odd frequencies so that the input signals are not mixed with the converted signals. Further embodiments of the present invention allows all the converted signals to be sent out through one fixed output port whether the input signals have even and odd frequencies (simultaneous conversion of multiple input signals), or whether the input signal changes between even and odd frequencies (sequential conversion of different input signals).

Fig. 6A shows such an arrangement of an optical signal converter in which all the converted signals are sent to one output port. Input signals are received by a separator 25 which separates the signals by sending the input signals of even and odd frequencies to an even frequency output port, marked "e", and an odd frequency output port, marked "o", respectively. The even frequency output port is connected to the input signal port of a first DFG 20A which also receives an energizing pumping signal is at frequency f_p1 so that the resulting converted signals are odd frequencies. Similarly, the odd frequency output port of the separator 25 is connected to the input signal port of a second DFG 20B which also receives an energizing pumping signal is at frequency f_p2 so that the resulting converted signals are even frequency signals. The converted signals of both DFGs 20A and 20B are sent to the input ports of an even/odd combiner 26. The odd frequency converted signals from the DFG 20A are received by the odd input port, marked "o", of the combiner 26, and the even frequency converted signals from the DFG 20B are received by the even input port, marked "e". The even/odd combiner 26 is simply an even/odd separator as described previously with its connections reversed. Any even frequency signals from the DFG 20A at the odd input port of the combiner 26 are rejected internally and any odd frequency signals from the DFG 20B at the even input port of the combiner 26 are also rejected. The combiner 26 combines the converted signals from the DFG 20A and from the DFG 20B at a common output port.

This arrangement separates the output converted signal(s) from the input signal(s) and works whether the input signal(s) have even or odd frequencies. The embodiment works with various pump frequencies, f_p1 (or $\frac{1}{2}*f_p1$ with second harmonic generation in the DFG) and f_p2 (or $\frac{1}{2}*f_p2$ with second harmonic generation in the DFG), for

the DFGs 20A and 20B as long as the pump frequencies allow the DFGs to convert the even frequency input signals to odd frequency output signals and vice versa.

One application of the Fig. 6A device is illustrated in Fig. 6B. Multiple input signals are converted simultaneously by one pump. The frequency grid reference frequency f_o is located arbitrarily near the center of the diagram. All the input signals at frequencies f_{s1}-f_{s4} are received by the input port of the separator 25 in Fig. 6A. Given the location of reference frequency f_o, f_{s1} and f_{s3} are even frequencies and leave the e output port of the separator 25. The DFG 20A converts these signals to odd frequencies f_{c1} and f_{c3}. Likewise, f_{s2} and f_{s4} are odd frequencies and leave the o output port of the separator 25 to be converted by the DFG 20A converts to signals at even frequencies f_{c2} and f_{c4}. The odd input port of the e/o combiner 26 receives the converted signals at frequencies f_{c1} and f_{c3} (and unconverted input signals at frequencies f_{s1} and f_{s3}), but since only frequencies f_{c1} and f_{c3} are odd, only the converted signals at these signals are passed to the common output port of the combiner 26. Likewise, the even input port of the e/o combiner 26 receives the converted signals at frequencies f_{c2} and f_{c4} (and unconverted input signals at frequencies f_{s2} and f_{s4}), but since only frequencies f_{c2} and f_{c4} are even, only the converted signals at these signals are passed to the common output port of the combiner 26. Thus the unconverted output signals have been separated or filtered from the input signals. A "band" of input signals at f_s has been converted to a band of converted signals at f_c.

Another application of the Fig. 6A device is illustrated by Fig. 6C. Instead of shifting or converting signals with a small set of wavelengths to a different wavelength set, there might be a need for converting a large set of signals in a wavelength (or frequency) range about a central point which is located within the range itself. Exemplary input signals in the range of frequencies, f_{s1}-f_{s13}, are to be converted about the central point frequency point $f_p/2$. (The central point frequency $f_p/2$ is sometimes called the "mirroring" frequency about which an input signal and its converted signal are mirrored. As discussed above, $f_p/2$ is one-half the pumping frequency for a DFG conversion process; alternatively, $f_p/2$ is the actual pump frequency for SHG:DFG and FWM conversion processes.) The input signals are shown in the top row of Fig. 6C. The signals converted from the input signals are shown in the bottom row of Fig. 6C and have frequencies, f_{c13}-f_{c1}, where the input signal at f_{s1} is converted to the converted signal f_{c1}, the input signal at f_{s2} to the converted signal at f_{c2}, and so on.

Because some of the frequencies of the converted signals are the same as the those of the input signals, for example, the input signal at f_{s4} has the same frequency as the

converted at f_{c11}, there is a problem in maintaining separation and preventing mixing of the input signals with the converted output signals. One solution to this problem is to use two conversion paths for the input signals. One way is to split the input signals about the frequency $f_p/2$ so that the signals at, say, higher frequencies than $f_p/2$ (labeled "blue" in Fig. 6C) travel down one path and are converted to signals at lower frequencies than $f_p/2$ (labeled "red" in Fig. 6C). The input signals at lower frequencies than $f_p/2$ ("red") travel down another path and are converted to signals at higher frequencies than $f_p/2$ ("blue"). This can done with an arrangement with the arrangement shown in Fig. 6A with the even/odd separator 25 and even/odd combiner 26 replaced by red/blue separators and red/blue combiners operative at the frequency $f_p/2$. The problem is the difficulty in creating a filtering device with an operating edge sharp enough to fit within one optical frequency grid spacing Δ. Typically there is the undesirable "dead band" problem caused by the insufficiently sharp edges in the filtering devices, i.e., the red/blue separators and combiners in this application.

A better solution is the Fig. 6A arrangement of the present invention. Rather than a "red/blue" separation, the separator 25 performs an even/odd separation of the input signals at frequencies f_{s1}-f_{s13} with the even frequency input signals going to the DFG 20A and the odd frequency input signals going to the DFG 20B. No matter what the particular conversion process, the DFGs 20A and 20B receive a pumping signal at a frequency such that the mirroring frequency is at $f_p/2$. The DFG 20A converts the even frequency input signals to the odd frequency output signals and the DFG 20B converts the odd frequency input signals to the even frequency output signals. The combiner 26 filters and combines the even and odd frequency output signals at its output port for the output frequency range, f_{c1}-f_{c13}.

Figs. 7A and 7B illustrate other arrangements which separates the output converted signal(s) from the input signal(s) and may be used in the applications described immediately above. The same reference numbers are used as in Fig. 6A to illustrate the similarity of operation of the referenced elements. The Fig. 7A arrangement has additional even/odd separators 21A and 21B respectively connected to the output of each DFG 20A and 20B. The separators 21A and 21B separates the converted signals from the input signals and the combiner 26 combines the converted signals from the DFGs 20A and 20B and sends them to the common output port. The combiner 26 also operates a filter, as described with respect to Fig. 6A, and provides for a second filtering level after DFGs 20A and 20B. In passing, the identical arrangement of the DFGs 20A and 20B and separators 21A and 21B and the arrangement of the elements of Fig. 5B are noted by the dotted line by Fig. 7A.

The Fig. 7B arrangement has additional even/odd separators 22A and 22B respectively connected between the initial separator 25 which receives all the input signals and the input of each DFG 20A and 20B. The separators 22A and 22B provide an additional filtering function on the separated input signals before they are respectively converted by the DFGs 20A and 20B. The combiner 26 combines the converted signals from the DFGs 20A and 20B and sends them to the common output port.

Another embodiment of the present invention is a particular definition or selection of the separator with respect to the pump frequency of a DFG. In some types of wavelength conversion, such as DFG, SHG:DFG and FWM processes described above, it is desirable to combine one or more input signals at particular wavelength(s) with one or more pump signals at particular wavelength(s). For example, in SHG:DFG process where the energizing pump signal is generated in the same device in which the input signal(s) is converted, the input signal(s) is combined with the actual pump signal at frequency $f_p/2$. In accordance with the present invention, this mirroring frequency is made to lie halfway between the grid locations of the signal frequencies. A suitably defined e/o separator as described above, but connected in reverse to form a combiner, can perform this function.

Returning to the calculations and above, the frequency f_s of the input signal must be located on the frequency grid so that

$$f_s = f_o + n_s\Delta \qquad \text{where } n_s \text{ is an integer}$$

about an arbitrary reference frequency f_o in the frequency grid of spacing Δ. As stated above, the frequency of the pump frequency f_p is:

$$f_p/2 = f_o + (n_p/2)*\Delta$$

wherein n_p is an odd integer. Thus, as stated previously, $f_p/2$ lies halfway between the frequencies of the grid. Alternatively, a smaller grid spacing could be defined as:

$$\Delta_p = \Delta/2 \qquad \text{so that}$$

$$f_s = f_o + 2n_s\Delta_p \qquad \text{and} \qquad f_p/2 = f_o + n_p\Delta_p$$

$$\text{or } f_s = f_o + n_s'\Delta_p \qquad \text{where } n_s' = 2n_s$$

As noted above, np is an odd integer and n_s is an even integer. If a new reference frequency grid is assumed where the grid spacing is Δ_p, then the frequencies of the input signals and converted signals lie at even multiples of the new grid spacing, and the frequency $f_p/2$ lies at an odd multiple of Δ_p. An even/odd separator which is sensitive to the

evenness/oddness of frequencies of this finer spaced grid, can be used to combine this input signal(s) and the pump signal at frequency $f_p/2$. Such a combiner 30, which is sensitive to the grid spacing $\Delta_p = \Delta/2$ with the assumption that the reference frequency f_o in the frequency grid of spacing Δ_p is that same as that in the frequency grid of spacing Δ, is illustrated in Fig. 8A. The output of the combined signals at the frequencies f_s and $f_p/2$ can be sent to a DFG for a wavelength conversion. Likewise, if the connections are reversed, a separator 31 is created, as illustrated in Fig. 8B. The separator 31 can receive signals from a DFG or other conversion at frequencies $f_p/2$, f_s and f_c, and separate the signal at $f_p/2$ from the signals at f_s and f_c due to the oddness or evenness of the multiples of the finer grid spacing Δ_p.

Another application of an off-grid pump frequency is where $f_p/2$ is ¼ way (or ¾ way as well) between the grid frequencies. If we have

$f_p/2 = f_o + (n_p/2)*\Delta + \Delta/4$ where n_p is an integer,

$f_s = f_o + n_s\Delta$ where n_s is an integer, and

$f_c = f_p - f_s$

We will then have

$f_c = f_o + (n_p - n_s)*\Delta + \Delta/2$

which will lie half way between the grid spaced at Δ. This conversion process is shown schematically in Figure 9.

In the conversion process shown in Fig 9, the resulting converted frequency grid has the same spacing as the input signal frequency grid, but is shifted by one-half the grid spacing. This process can act as a frequency shifter of the whole set of frequencies at once.

Another advantage of the conversion process shown in Fig 9 is the fact that, because the converted frequencies lie off the original input signal grid, there is no problem with frequencies colliding and mixing. The whole set of input frequencies can be converted in one device, even with $f_p/2$ lying within the range of the input set, without having to separate the input frequency set into two groups.

As shown in Fig. 10a, for the conversion process as run in the previous case, where $f_p/2$ is at ¼ or ¾ grid spacing, the output converted signals can be separated from the input signals using another e/o separator. However, this e/o separator is meant for a grid spacing of ½ the spacing of the original signals.

The same separation process as shown in Fig. 10a can be accomplished with the e/o separator used in reverse so that the unconverted signals may be separated or lost

internally to the e/o separator. This approach is illustrated in Fig. 10b. In this fashion, the use of additional filters are may be obviated.

Further, the configuration shown in Fig 10b can be used to combine the output converted signals with a new set of signals on the original grid spacing Δ. This approach is shown in Fig 11 and enables: signals In1 to be simultaneously converted through DFG to a shifted grid; the separation of the input In1 signals from the output converted In1 signals; and the combining of the In2 signals with the output converted In1 signals. In this fashion, the combined output of the e/o combiner may have frequencies on a grid with frequency spacing Δ/2. In this fashion, all-optical frequency shifting and grid combining is accomplished by a process of DFG and interleaving. In practice, some power balancing of the two sets of signals may be required, and can be accomplished with an amplifier following the DFG or elsewhere in the system.

Therefore, while the invention has been described by way of example and in terms of the specific embodiments, it is to be understood that the invention is not limited to the disclosed embodiments. To the contrary, it is intended to cover various modifications and similar arrangements as would be apparent to those skilled in the art. Therefore, the scope of the appended claims should be accorded the broadest interpretation so as to encompass all such modifications and similar arrangements.